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by

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16. ABSTRACT

Previous laboratory experiments and numerical modeling have identified characteristics of plume dispersion in the highly convective mixed layer that deviate significantly from predictions of Gaussian models. To assess the validity of these observations, meteorologists conducted a field study named CONDORS (Convective Dispersion Observed with Remote Sensors). Since detailed and accurate vertical profiles of a plume are necessary for testing the significant conclusions of the models, the primary tracer measurements in CONDORS were performed by a lidar and radar. These scanning remote sensors are able to map out at regular time intervals the three-dimensional distribution pattern of particles appropriate for backscattering each instrument's electromagnetic radiation. Direct comparisons with model results are then possible. CONDORS demonstrated that radar measurements of chaff under convective conditions and lidar measurements of oil fog can succeed in describing not only general plume location and shape, but also relative tracer concentrations. With sufficient care in tracer generation, sensor operation, and signal processing, the tracer systems are semiconservative and losses that do occur can be reasonably balanced.

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FIELD MEASUREMENTS IN THREE DIMENSIONS OF PLUME DISPERSION IN THE HIGHLY CONVECTIVE BOUNDARY LAYER

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1. INTRODUCTION

Laboratory experiments by Willis and Deardorff (e.g., 1978, 1981) and numerical modeling by Lamb (e.g., 1978) have identified characteristics of plume dispersion in the highly convective mixed layer that deviate significantly from predictions of Gaussian models. They observed, for instance, that the vertical location of maximum concentration from an elevated source initially descends to near the surface rather than remaining level with the release height, which results in larger maximum surface concentrations than produced by a Gaussian plume model. The Gaussian formulation describes their lateral distributions very well. The CONDORS (CONvective Dispersion Observed with Remote Sensors) project is an attempt to confirm the validity of the model predictions of Willis and Deardorff (hereafter WD) and of Lamb in the convective boundary layer. Moninger et al. (1983) and Eberhard and Lavery (1984) described some results from the successful preliminary phase that occurred during autumn 1982 at the Boulder Atmospheric Observatory (BAO). This report emphasizes the main phase of CONDORS during autumn 1983, which was also held at the BAO.

Since detailed and accurate vertical profiles of the plume are necessary for testing the significant conclusions of the models, the primary tracer measurements in CONDORS were performed by a lidar and radar. These scanning remote sensors are able to map out at regular time intervals the three-dimensional distribution pattern of particles appropriate for backscattering each instrument's electromagnetic radiation. Direct comparisons with model results are then possible. In our experiment we used the same scaling parameters as WD to nondimensionalize the results that apply to a mixed layer dominated by buoyancy-induced turbulence. The convective velocity scale is

$$w^* = (\overline{w'T'}\, z_i\, g/T)^{1/3} \qquad (1)$$

where $\overline{w'T'}$ is the heat flux at the surface and z_i is the height of the mixed layer. The height z, the downwind distance x, and time t are made nondimensional by

$$Z = z/z_i \qquad (2)$$

$$X = (w^*/U)(x/z_i) \qquad (3)$$

$$\tau = t\, U/z_i \,. \qquad (4)$$

The mean wind speed U must be large enough to make streamwise diffusion negligible, but small enough to keep the contribution of shear-induced turbulence in the bulk of the mixed layer small compared with turbulence induced by surface heating. CONDORS was designed to measure plume dispersion within these limits. This design is briefly described, followed by some examples of preliminary results and comparisons with model predictions.

2. MEASUREMENTS

The locations of meteorological and tracer instruments during the autumn 1983 experiments are shown in Fig. 1. The sensors at each of eight levels on the BAO tower included a three-axis sonic anemometer for wind and turbulence and a fast-response temperature probe. For each analysis period, U was obtained by averaging the wind speeds at 150, 200, 250 and 300 m, while $\overline{w'T'}$ is the average of the values measured at 10 and 22 m. An instrument carriage on the west side of the tower served as a platform for elevated releases. The gas samplers were on a single arc about 1.2 km distance and at 5° intervals in bearing from the tower.

The oil foggers sprayed oil into a hot jet of air, where it evaporated and then later recondensed when mixed with the cooler external air. Oil flow was typically 35 gs^{-1}. Calculated plume rise had an upper bound of 13 m. Since virtually all of the drops had diameters less than 10 μm, gravitational settling was negligible.

The chaff generator produced about 40,000 separate filaments per second of aluminum-coated

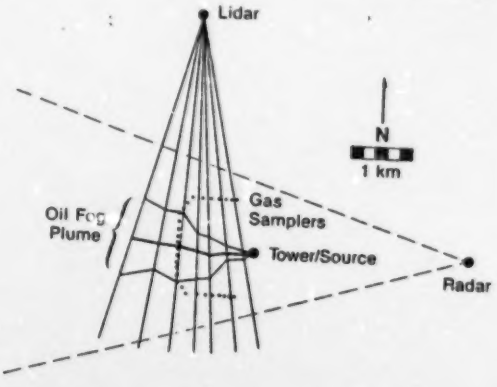

Fig. 1. Experiment layout for CONDORS in 1983. The centerline and edges (10% of cross-section peak) of the vertically integrated plume are shown for period A.

Mylar 1.6 cm in length. Their terminal velocity of 0.3 m s^{-1}, which can be compared with typical w* values of 1.6 m s^{-1}, was large enough to require consideration during analysis. These two tracers were independent because neither the lidar nor radar could detect the other sensor's particles.

The lidar performed a repeating series of vertical scans at typically six azimuth directions, the farthest about 2 km downwind of the source. Figure 1 illustrates the scan locations for one run, labeled period A. During post-processing the oil fog distributions were extracted through an interactive graphics program. After reviewing a scan, a staff member entered instructions to achieve correct processing. The program compensated for attenuation by haze and the plume. It then subtracted the background signal from the haze. The resulting plume concentrations were then interpolated to a $(50\ m)^2$ or finer rectangular grid in each scan plane. Scans at the same azimuth during an analysis period were then averaged together.

The radar measured the chaff throughout the volume of the plume with a repeating series of azimuthal scans at steps in elevation angle. Figure 1 shows the limits of the azimuthal scan for one run. Batch rather than interaccive post-processing was used. Radar ground clutter replaced the lidar's attenuation and haze background as the largest contaminating factor to be removed. Interpolation was to a $(50\ m)^3$ cubic grid aligned with the mean wind direction.

The principal gaseous tracer was SF_6, which was released coincident with the elevated chaff release. The oil fog was usually released from the surface but was sometimes coincident with the chaff and SF_6. Bag samplers operated essentially continuously (pump cycle of 2 s on and 5 s off) for each day's run of 2 hours. Tracer releases began 10 min before sampling commenced. Table 1 lists typical resolution (full width at half maximum) and sampling intervals for each tracer system.

The field measurements should last long enough for the averaged data to adequately represent the ensemble average. Table 2 gives the nondimensional duration for all analyzed periods from 1982 and 1983, segregated by approximate source height z_s/z_i. The durations are also given of WD's water tank experiments. The effective duration for the lidar is somewhat less for some runs because the scan interval in t and x was too large to resolve even crudely each large eddy. The field durations are adequate for a reasonable comparison with the water tank results, although more at $z_s/z_i = 0.25$ would have been desirable.

3. EXAMPLE RESULTS

A few selected results illustrate the consistency among tracers, and how individual runs compare with WD's results. These comparisons are preliminary because only one method rather than a consensus of several methods has been applied in determining z_i. Also, no compensation has been applied for low-elevation blockage of the radar and lidar. We highlight period A (1310-1350 MST on September 7, 1983) because all tracer releases were coincident at $z_s = 265$ m, wind direction and meteorological steadiness were excellent, and the instruments performed well. Scaling parameters for period A were $z_i = 865$ m and $z_i U/w^* = 2610$ m.

TABLE 1. Typical tracer sampling resolutions and intervals.

Item	Vertical	Cross-wind	Down-wind	Time
Radar				
resolution	70 m	160 m	90 m	instantaneous
interval	70 m	90 m	37.5 m	135 s
Lidar				
resolution	2 m	12 m	2 m	instantaneous
interval	10 m	3 m	380 m	210 s
Gas				
resolution	point	point	point	continuous
interval	---	100 m	---	600 s

TABLE 2. Elapsed time (nondimensional) of tracer data.

z_s/z_i	$\tau = t\ U/z_i$			
	oil fog	chaff	gas	water tank
0.0-0.1	28	10	3	28
0.1-0.2	7	7	10	0
0.2-0.3	6	15	15	28
0.3-0.4	52	52	34	0
0.4-0.5	29	29	10	28

With careful tracer production, sensor operation, and signal processing we were able to achieve trustworthy concentration patterns of oil fog and chaff. Figure 2 provides evidence for this by showing the total signal in the cross-sections as a function of distance x. This was accomplished by integrating the inferred concentration $c(x,y,z)$ in the vertical and horizontal to produce $c_{yz}(x)$. The results are normalized by the peak value for each run. A perfectly conservative tracer would yield an essentially constant c_{yz} if averaging time were long. The chaff data are typical for all periods. The initial increase near the source was caused mostly by saturation of the radar receiver by strong signal but also by removal of some plume together with the ground clutter generated by the tower. The total signal decreased steadily beyond the peak, which is consistent with deposition loss, increasing blockage of return from near the surface by intervening terrain, and drop of signal from diffuse portions of the plume to below the radar noise threshold. Oil fog c_{yz} typically declined near the source for the elevated releases and then leveled off somewhat. We attribute this behavior mainly to partial evaporation of the drops, a process that decelerates as the larger and less volatile molecules are left behind. The oil used during 1982 had greater volatility, and c_{yz} declined even more than in Fig. 2. A second factor in the decline is loss of diffuse portions of the plume into the threshold set by the background haze signal. The ground releases typically exhibited an initial increase in c_{yz} because a significant fraction of dense plume remained below the lidar's lower scan

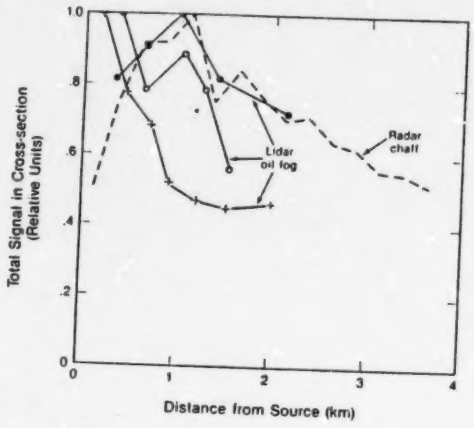

Fig. 2. Changes in $\overline{c_{yz}}$ with downwind distance x: period A chaff (---) and oil fog (+), period B oil fog (o), and a surface release of oil fog (•).

limit. These data indicate that the oil fog and chaff can be considered semiconservative and that it is reasonable to account for gradual changes by normalizing with $\overline{c_{yz}}(x)$.

A comparison of profiles of SF_6 and nearby oil fog provides further support for trusting the distributions of oil fog concentrations. In the data of Fig. 3, the conversion factor between release rate (q) of the oil and lidar backscatter was empirically determined by

$$K(x) = \overline{c_{yz}}(x)\ U/q \ . \qquad (5)$$

The oil fog profile was from the azimuth nearest the west side of the gas sampler arc (Fig. 1), and furthermore only the vertical segment between about 22 to 72 m above the surface. The integral of this near-surface oil fog profile was 16% greater than the SF_6 profile. The agreement in Fig. 3 is very good considering the differences in the sampling methods.

Horizontal profiles of vertically-integrated concentrations $\overline{c_z}(x,y)$ for oil fog and chaff during period A are shown in Fig. 4. The discrepancies in details can be attributed to differences in sampling times and positions. The two tracers are very consistent in these horizontal profiles.

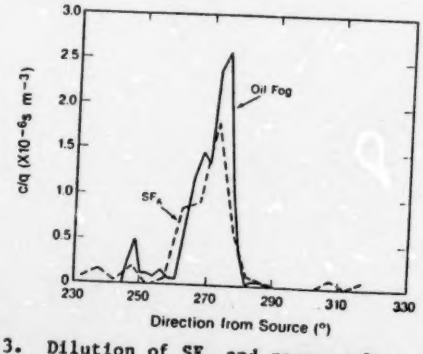

Fig. 3. Dilution of SF_6 and near-surface oil fog during period A.

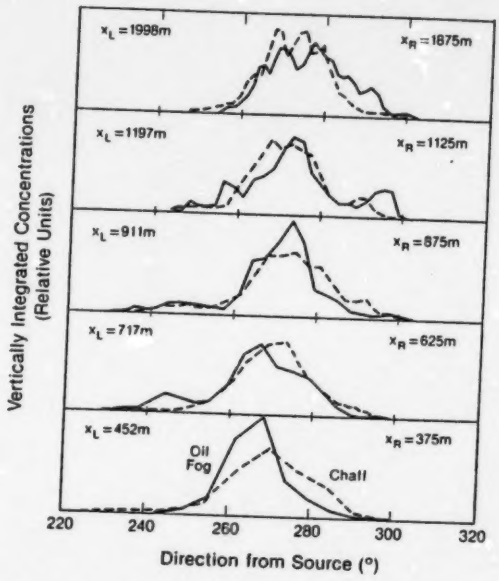

Fig. 4. Horizontal profiles of $\overline{c_z}$ for period A: oil fog (——) and chaff (---). The downwind distances x (in meters) have subscripts L for lidar and R for radar.

Vertical profiles of the horizontally integrated concentrations $\overline{c_y}(x,z)$ for the same period do not match quite as well (Fig. 5). The area under both curves of each pair is the same, with the plot of each pair then normalized to peak value. The chaff appears consistently lower than the oil fog, which can be explained by gravitational settling of the chaff, noncoincident sampling, and possible misalignment of the radar by a fraction of its 70 m vertical resolution. The results from the tank model for a similar

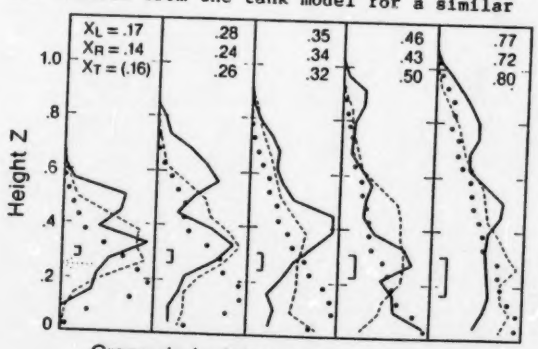

Fig. 5. Vertical profiles of $\overline{c_y}$ for period A in nondimensional coordinates: oil fog (——) and chaff (---). Results from WD (1978) are shown with large dots for comparison, with a dotted arrow marking their $z_s/z_i = 0.24$. Subscripts L and R are as in Fig. 4, and T refers to tank results. The brackets show predicted chaff fall distance. The top of the bracket is at the BAO release height. WD results at $X_T = 0.16$ are an average of published results at $X_T = 0.12$ and 0.20.

release height, with each profile normalized by peak value, clearly reveal a descent of the locus of maximum $\overline{c_y}$ to the surface at X = 0.5. The field data, however, reveal an initial lifting followed by a descent to the surface. Since a single field run is not adequately representative, Fig. 5 should not be interpreted as disproof of WD's results. In fact, the example of Moninger et al. (1983) shows excellent agreement with the water tank model for one 1982 period. Another example of very good agreement for an individual period is in Fig. 6, which shows oil fog profiles from period B (1050-1130 MST on September 6, 1983), where z_s = 280 m, z_i = 980 m, and $z_i U/w^*$ = 1470 m. The oil fog maximum descended to the surface, albeit at larger X than the tank results.

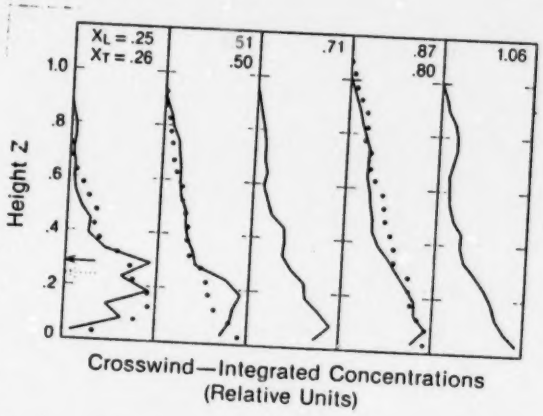

Fig. 6. Vertical profiles of $\overline{c_y}$ for oil fog during period B and WD (1978). See Fig. 5 for the legend, except a solid arrow marks the oil fog source height.

4. SUMMARY

The CONDORS experiment produced a valuable data set for study of dispersion in the highly convective boundary layer. Analysis is in progress to nondimensionalize and combine similar field periods and compare the results with WD's water tank and Lamb's numerical models. A data report now under preparation will also make CONDORS results available to other interested researchers. Among the drawbacks of CONDORS is the variety of nondimensional release heights in spite of our efforts to duplicate those chosen by WD. The effect of chaff fall velocity must also be accounted for, particularly at x > 2.5 km where the oil fog data terminated. In spite of these problems, CONDORS provided a wealth of vertical profile data combined with excellent supporting meteorological measurements.

CONDORS also demonstrated that radar measurements of chaff under convective conditions and lidar measurements of oil fog can succeed in describing not only general plume location and shape, but also relative tracer concentrations. With sufficient care in tracer generation, sensor operation, and signal processing the tracer systems are semiconservative, and losses that do occur can be reasonably compensated for.

5. ACKNOWLEDGMENTS

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